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An alternative approach to experimental simulation of wind characteristics in urban environments

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Abstract

The classical Counihan vortex generators for wind-tunnel simulations of the atmospheric boundary layer (ABL) flow were redesigned to experimentally simulate natural wind characteristics in urban environments. Three redesigned (truncated) vortex generators, a castellated barrier wall and a fetch of roughness elements were employed to reproduce a lower portion of the neutrally stratified ABL developing above an urban type terrain. A hot-wire anemometry system was used to measure mean velocity and velocity fluctuations. Investigated parameters were mean velocity, turbulence intensity, integral length scale of turbulence, and power spectral density of velocity fluctuations. Experimental results indicate that the truncated vortex generators developed for this study can be successfully employed in urban ABL part-depth wind-tunnel simulations, as they compare well with commonly applied empirical models and wind specifications for urban type terrain given in the ESDU 74031 data sheets.

Keywords: Atmospheric boundary layer flow, wind-tunnel simulation, urban environment, hot-wire anemometry

1. Introduction

The Counihan [1] method (barrier, vortex generators and surface roughness) has been frequently used for atmospheric boundary layer (ABL) simulations in the wind tunnel. Using this method, the so called full-depth ABL simulations can be created, representing the wind characteristics throughout the entire depth of the ABL, say up to 500 - 600 m. This approach has been commonly used for simulating specific wind-related problems of structural objects that reach deeply into the ABL. Full-depth ABL simulation enables 'capturing' wind characteristics around the whole structural object, but small-scale details of the flow cannot be reproduced in great detail.

In this study, a new type of vortex generator (Figure 1) has been developed to enable a more precise simulation of urban wind characteristics in lower atmospheres (part-depth ABL simulation). The main assumption of the present work is that the original Counihan vortex generators would not be able to produce enough turbulence when trying to create a part-depth urban ABL wind-tunnel simulation, say up to 100 - 200 m. In general, a wind-tunnel ABL

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simulation is considered to be comparable to atmospheric conditions when the experimental results from the wind tunnel agree well with the full-scale measurements as well as with the accepted empirical and theoretical models reported in literature. In particular, the parameters commonly checked for consistency within a simulated ABL flow are mean velocity, turbulence intensity, turbulent Reynolds shear stress, integral length scales of turbulence, and power spectral density of velocity fluctuations.

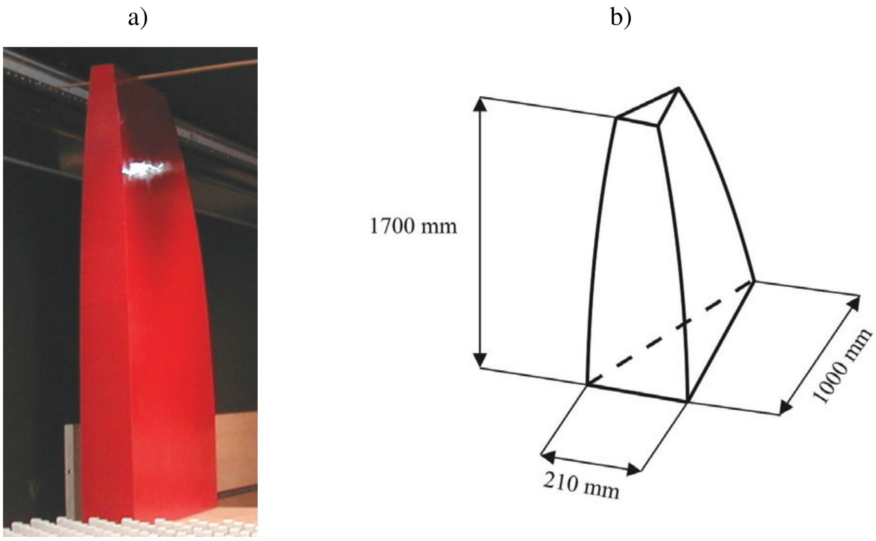

Figure 1. Applied truncated vortex generator (one in a set of three pieces): a) photograph taken in the wind-tunnel test section, b) schematic view with dimensions

The width and length of applied vortex generators were calculated according to Counihan [1] for 2 m high vortex generators, and vortex generators were afterwards truncated at 1.7 m. This approach allows a better resolution of airflow characteristics in the lower ABL wind-tunnel model, which is particularly important in studies on distribution of air pollutants in urban environments. This study attempts to complement previous experiments dealing with influence of spacing between buildings on wind characteristics (Ref. [2]) and scale effects in wind tunnel modeling of an atmospheric boundary layer (Ref. [3]).

2. Experimental setup

The experiments were carried out in the boundary layer wind tunnel ('Rudolf-Frimberger-Windkanal') at the Faculty of Mechanical Engineering, Technische Universität München (TUM). This wind tunnel has a 1.80 m high, 2.70 m wide and 21 m long test section. The air driven by a 210 kW electric motor enters through a 2.11:1 contraction, passing through a honeycomb and screens before reaching the test section. The rotating table for placing structural models is located 11.3 m downwind from the contraction exit. The upper wall of the test section can be displaced vertically to allow conditions of zero pressure gradient boundary layers. The facility can be operated in closed/open circuit mode with velocities up to 30 m/s. More technical details about this wind tunnel can be found in Refs. [4] and [5]. It needs to be mentioned that this wind tunnel was designed for experimental simulations of the ABL flow, and it is not capable of simulating transient winds, as some other recently developed facilities (e.g. transient flow field simulators at University of Notre Dame and Iowa State University in USA, and at Miyazaki University, Japan). In the present study, the lower urban ABL was reproduced in the wind tunnel using a set of three newly developed vortex generators together with the castellated barrier wall and a fetch of surface roughness elements. This approach for ABL wind-tunnel simulation has been adopted by Counihan [1], and the original Counihan vortex generators have been truncated for the purposes of this study. In principle, as the uniform air flow with very low turbulence intensity comes out of the nozzle, streams over the castellated barrier wall, vortices with

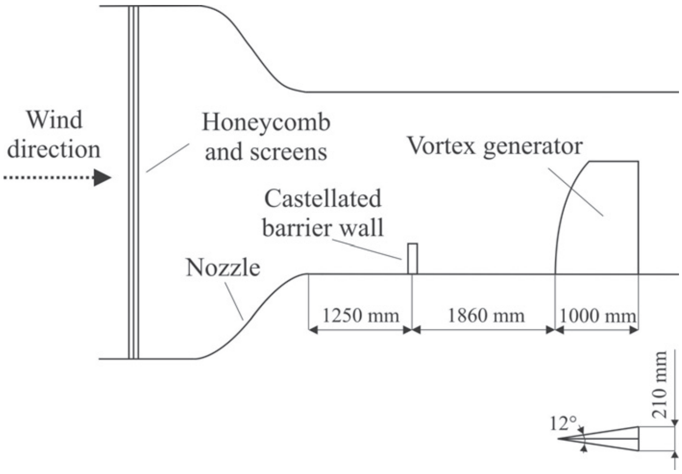

Figure 2. An arrangement of the castellated barrier wall and truncated vortex generators in the wind-tunnel test section

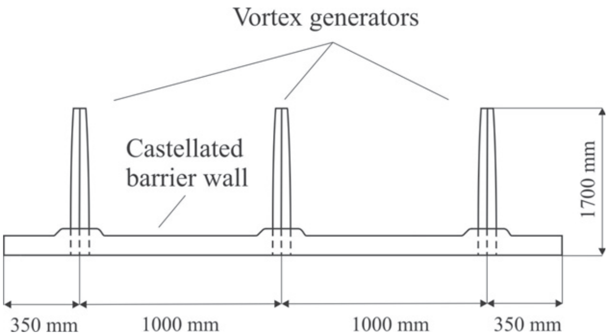

Figure 3. Design details of the vortex generators and castellated barrier wall in the wind-tunnel test section; basic barrier height (without castellation) is 292 mm, total barrier height (including castellation) is 376 mm

horizontal axes of rotation are generated and the initial momentum defect in the boundary layer is produced. Further downstream vortices with vertical axes of rotation develop as air flows around truncated vortex generators. Behind the vortex generators, the test section floor is covered with surface roughness elements which provide the sustained formation of boundary layer structures. An arrangement of the simulation hardware in the wind-tunnel test section is presented in Figures 2 and 3. Velocities were measured using the triple hot-wire probe DANTEC 55P91. This sensor was operated in constant temperature mode using a ten-channel anemometer system AALAB AN 1003. The measurement uncertainty of the anemometer system was reported in Breitsamter [6]. Velocity time series were obtained by sampling the anemometer bridge outputs of the probe sensor at 1.25 kHz with a record length of 150 s. Measurements were taken from 18 measuring points placed along a vertical line down the centre of the turntable. Results are reported in the form of mean velocity, turbulence intensity, integral length scale of turbulence, and power spectra of velocity fluctuations.

Scaling-down of the mean winds and atmospheric turbulence from the full-scale into the wind tunnel was carried out using the criteria reported in Plate [7]. In particular, it was attempted to create an urban ABL simulation, which would satisfy Jensen similarity ($Je=\delta/z_0$ or $Je=h/z_0$, where Je is the Jensen number, δ is the ABL thickness, h is the building height, z_0 is the aerodynamic surface roughness length), and $u_\tau \cdot z_0 / \nu > 5$, where u_τ is friction velocity and ν is kinematic viscosity. The generated ABL wind-tunnel simulation was validated by comparing the obtained experimental results with the ESDU 74031 [8] data sheets and accepted empirical models.

3. Results

All heights and lengths were scaled-up from wind tunnel to full-scale dimensions using the length scale factor 1:210 calculated as suggested by Cook [9]. This length scale factor was calculated using the aerodynamic surface roughness length z_0 and the longitudinal integral length of turbulence ${}^{x}L_u$,

$$S = 91.3(z-d)^{0.491} / {}^{x}L_u^{1.403}\, z_0^{0.088}, \tag{1}$$

where S is the simulation length scale factor, z is vertical distance from wind tunnel floor, d is displacement height.

Figure 4 shows good agreement of recorded mean velocities with the power-law for the power-law exponent α = 0.35, which can be accepted for the representation of the urban ABL. In general, power law is defined as

$$\frac{\overline{u}_z}{\overline{u}_{ref}} = \left(\frac{z-d}{z_{ref}-d}\right)^{\alpha}, \tag{2}$$

where z is vertical distance from wind tunnel floor, d is displacement height, z_{ref} is reference height, $\overline{u}_z$ is mean velocity component in the x-direction at height z, $\overline{u}_{ref}$ is reference velocity, α is power-law exponent.

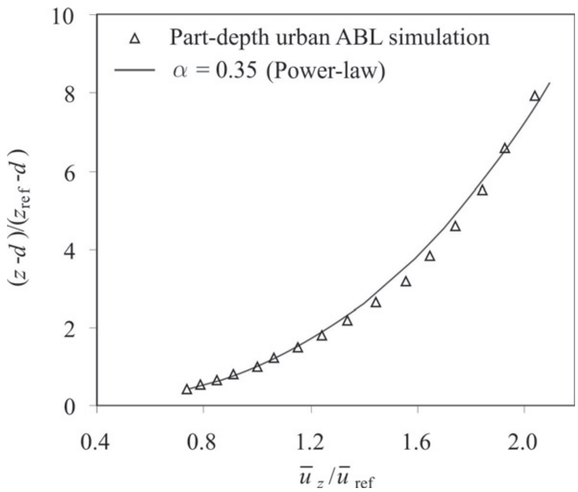

Figure 4. Mean velocity profile in longitudinal direction, linear presentation

In Figure 4, reference height z_{ref} is 17 cm at wind-tunnel scale (35 m full-scale), reference velocity $\overline{u}_{ref}$ is 10.1 m/s, displacement height d is 2.8 cm at wind-tunnel scale (5.9 m full-scale). As Dyrbye and Hansen [10] indicated that urban areas with at least 15% of the surface covered by buildings with an average height exceeding 15 m are characterized with velocity profiles with the power law exponent α = 0.30, the urban ABL wind-tunnel simulation in this study would imply slightly more spacing density of buildings and/or higher ground obstructions than in the urban ABL reported by Dyrbye and Hansen [10].

Figure 5 shows good agreement of recorded mean velocity profile with the logarithmic law in lower 100 m of the ABL wind-tunnel simulation. The logarithmic law is given as

$$\frac{\overline{u}_z}{u_\tau} = \frac{1}{\kappa}\ln\frac{z-d}{z_0}, \tag{3}$$

where κ is von Kármán constant equal to 0.4. In general, agreement of mean flow field of the ABL wind-tunnel simulation can be assumed to be in good correspondence with full-scale conditions when mean velocity profiles recorded in the wind tunnel agree with the power-law throughout the entire depth of the ABL wind-tunnel simulation. In addition, wind-tunnel results for mean velocity in longitudinal direction should compare well with the logarithmic law throughout the lower 100 m of the atmosphere, whereas this height is scaled-up from the wind tunnel to full-scale using the adopted length scale factor. The observed trends are in agreement with recommendations by Dyrbye and Hansen [10].

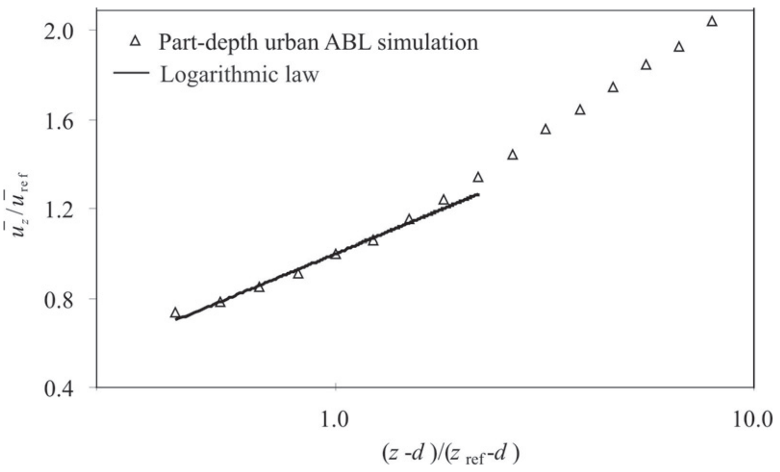

Figure 5. Mean velocity profile in longitudinal direction, logarithmic presentation

As distribution and dilution of air pollutants in urban environments strongly depend on characteristics of atmospheric turbulence, it was attempted to correctly reproduce profiles of turbulence intensity, integral length scale of turbulence and power spectra of velocity fluctuations using the modified experimental hardware. Turbulence intensity and integral length scale profiles were compared with the ESDU 74031 [8] data sheets, which represent a compilation of previous full-scale results recorded in the atmosphere.

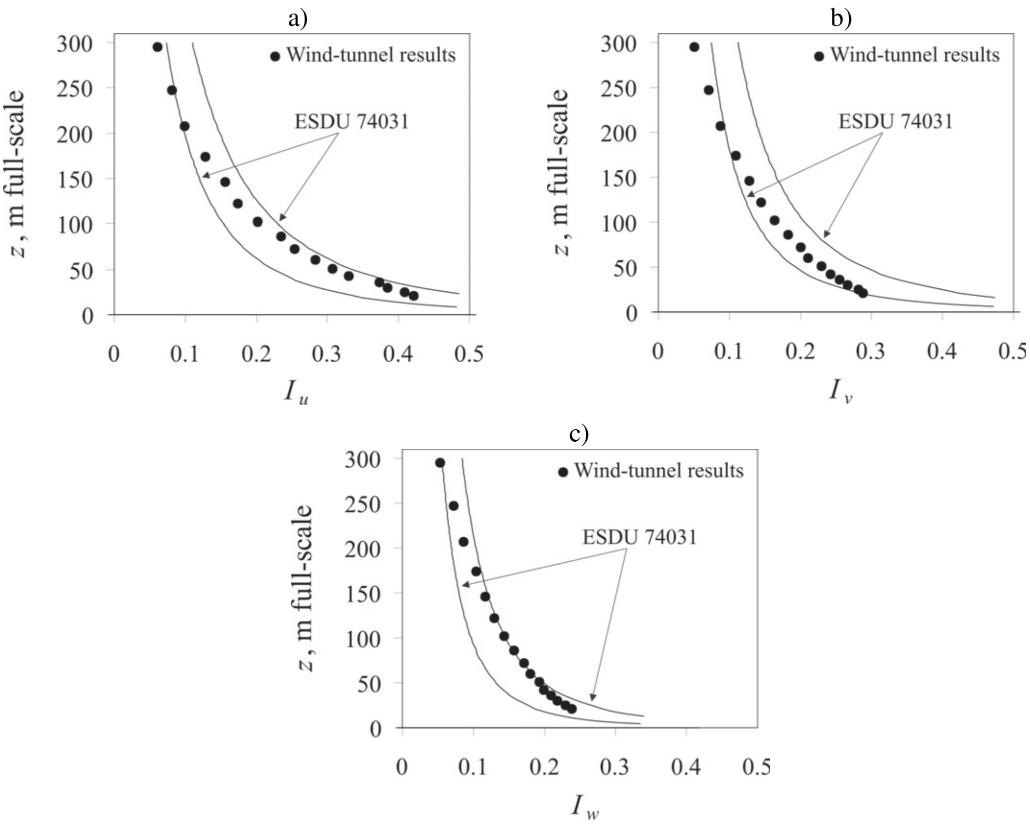

Figure 6. Turbulence intensity I_u, I_v, I_w profiles for part-depth urban ABL simulation in comparison with the ESDU 74031 [8] data sheets

Figure 6 shows a good agreement of turbulence intensity I_u, I_v, I_w profiles recorded in the wind-tunnel with ESDU 74031 [8] data recommended for aerodynamic surface roughness length z_0 = 1.9 m. Wind-tunnel data were normalized to the mean velocity at the corresponding measuring point. In this study, z_0 = 1.9 m and d = 5.9 m full-scale, and α = 0.35 were recorded. ESDU 74031 [8] scatter bands for turbulence intensity profiles in Figure 6 represent ±20 of the recommended values in ESDU 74031 [8], as this scatter of wind-tunnel values is acceptable in practice, as suggested in ESDU 74031 [8].

Figure 7 shows profiles of the ${}^xL_u$ ${}^xL_v$, ${}^xL_w$ longitudinal integral length scales of turbulence recorded in the wind tunnel in comparison with ESDU 74031 [8] data. Integral length scales of turbulence were calculated using autocorrelation functions and assuming the validity of Taylor's hypothesis (frozen turbulence). ESDU 74031 [8] scatter bands for ${}^xL_u$ ${}^xL_v$, ${}^xL_w$ profiles in Figure 7 represent ±30 of the recommended values in ESDU 74031 [8], as suggested in ESDU 74031 [8].

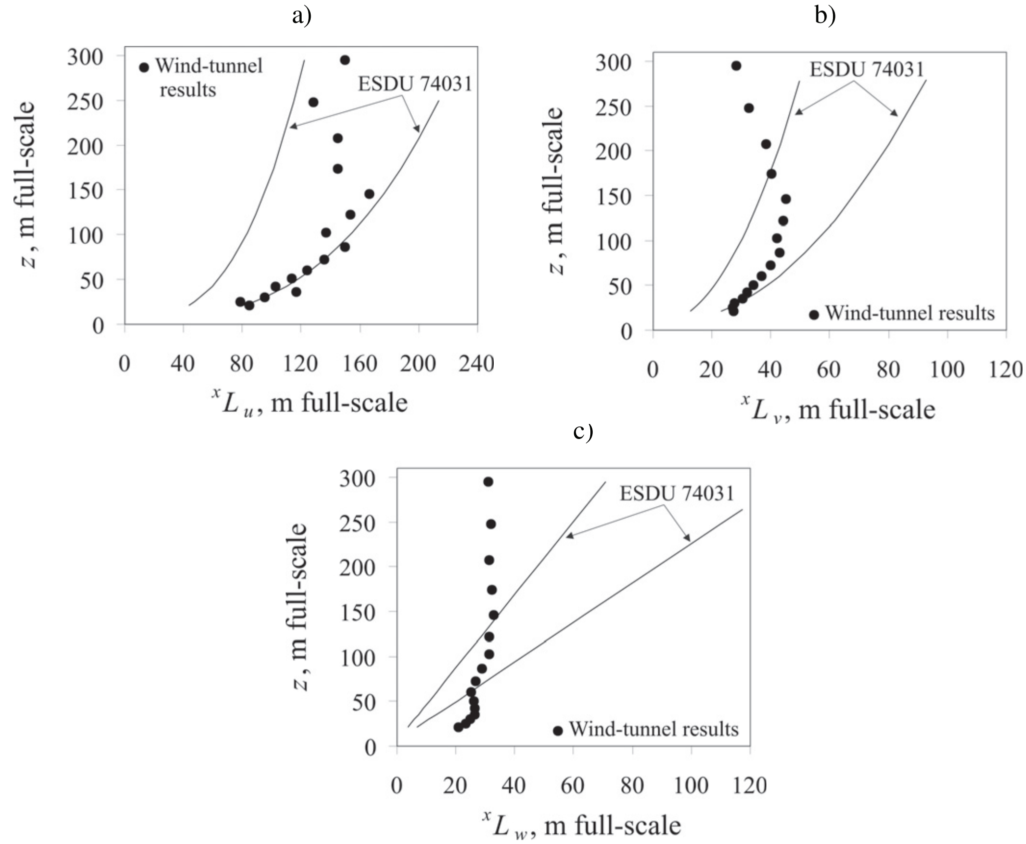

Figure 7. Profiles of the ${}^xL_u$ ${}^xL_v$, ${}^xL_w$ integral length scales of turbulence in comparison with the ESDU 74031 [8] data sheets

In general, the ${}^xL_u$ ${}^xL_v$, ${}^xL_w$ profiles compare well with ESDU 74031 [8]. However, obtained ${}^xL_u$ ${}^xL_v$, ${}^xL_w$ values increase in the near-ground region and they remain nearly constant with further increase in height. This trend was reported in other wind-tunnel studies as well (e.g. Farell and Iyengar [11]) and is possibly due to different mechanisms of boundary layer development in the wind tunnel and in the full-scale (Ref. [3]). Furthermore, it is particularly difficult to incorporate larger eddies into the wind-tunnel boundary layer, as the confined cross-section dimensions of the wind tunnel test section do not allow large eddies fully to develop (Peterka et al. [12]).

The power spectral density of longitudinal velocity fluctuations at z = 100 m full-scale reported in Figure 8 agrees very well with theoretical models of Kolmogorov [13] and von Kármán [14] indicating a path of wind-tunnel turbulence energy distribution similar to full-scale atmospheric turbulence; f is frequency, $S_u(f)$ is power spectrum of longitudinal velocity fluctuations, $\sigma_u(z)$ is standard deviation of absolute velocity in the x-direction u. In general, turbulence consists of eddies of many different length scales, whereas most of the kinetic energy of the turbulent motion is contained in large eddies. Due to impingement and friction of eddies to each other, energy dissipation takes place. In the mid-frequency part of the velocity power spectra called inertial subrange, energy dissipation process from large eddies to smaller ones follows the Kolmogorov [13] law. This process continues, resulting in creation of smaller and smaller eddies and producing a hierarchy of eddies, a so-called energy cascade. Finally, turbulent eddies in high-frequency range become small enough so that molecular diffusion becomes dominant and dissipation of smallest eddies occurs. In ABL wind-tunnel simulations it is considered to be one of the key issues to properly reproduce Kolmogorov's energy cascade in the inertial subrange of the velocity power spectra, as that turbulence feature significantly determines patterns of air pollutant dispersion, wind loading of structures, etc.

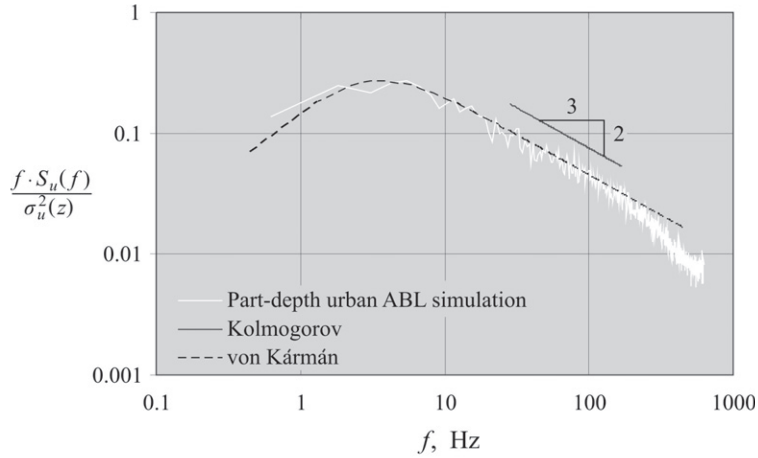

Figure 8. Power spectral density of longitudinal velocity fluctuations at z = 100 m full-scale

4. Concluding remarks

A wind-tunnel study has been carried out to investigate characteristics of redesigned Counihan vortex generators in experimental simulations of the neutrally stratified urban ABL flow. The simulation hardware included three truncated Counihan vortex generators, a castellated barrier wall and a fetch of roughness elements. The main assumption of the present work is that the original Counihan vortex generators would not be able to produce enough turbulence when trying to create a part-depth urban ABL wind-tunnel simulation. A hot-wire anemometry system was used to measure mean velocity and velocity fluctuations. Investigated parameters were mean velocity, turbulence intensity, integral length scale of turbulence, and power spectral density of velocity fluctuations. Experimental results indicate that the truncated vortex generators developed for this study can be successfully employed in urban ABL part-depth wind-tunnel simulations, as they compare well with commonly applied empirical models and wind specifications for urban type terrain given in the ESDU 74031 data sheets.

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